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PROBLEMS OF CLASSIFYING FAILURES OF MACHINES AND THEIR COMPONENTS

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R. V. Kugel'
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Vestnik Mashinostroyeniya No. 1, pp. 13-18 (1966)

Translated from the Russian

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Because of the increased attention paid to the problem of reliability of machine-building products, to organization of tests and observation of the performance of products in operation, and also to the analysis of the results of observations by using the methods of the theory of reliability, there inevitably appears a series of problems pertaining to the nature of failures, their classification, recording, and analysis. Discussed in this paper are the fundamentals of these problems; for example, what is a failure, can any specific event be regarded a failure? How should the failures appearing during the operation of a complex multicomponent machine be classified? Do all failures deserve the same attention, accounting, and recording? Which of the failures should be used as a basis for estimating the faultless performance and the service life of a machine?

A failure is generally known as a complete or partial loss by a product of its ability to perform; i.e., it is a state at which the product corresponds at a given moment of time to all requirements established for all basic parameters which characterize the normal execution of the specified functions.[1] It means that, when the appearing defect affects only the minor parameters of the product without impairing its normal work, it should be regarded as a defect in the product, but not as a failure; in such a case, the faultiness of a machine, as a whole, can be also regarded as the failure of one of its components.

Failures can be classified from different points of view, by different symptoms, and in accordance with the pattern shown in the table. According to the latter, a distinction should be first made between failures appearing under normal (where the rules for using and servicing of the machine are complied with) and under abnormal operating conditions. From now on, while considering only the failures appearing under normal operating conditions, for the failures appearing under abnormal conditions we will confine ourselves by remarking that all of them can be divided into failures caused by incorrect

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[1]"The Reliability of Technical Systems and Products," Collection of Recommended Terms of the Committee on Scientific and Technical Terminology of the Academy of Sciences, USSR, Nauka (Science), No 67a, 1965.

Classified Group	Classifying Symptom	Failure
1	Originating conditions	Appeared under normal or under abnormal conditions
2	Causes of failures	Not caused by destruction; due to destruction
3	Possibilities of further use of product	Entirely possible; only partly possible
4	Character of change in product's parameters	Sudden; gradual
5	Presence of external manifestations	Obvious (explicit); hidden (implicit)
6	Relationship between the failures of components of the product	Independent; dependent
7	Consequences	Dangerous; safe; heavy; light
8	Method of eliminating	By replacing the part, by adjusting, cleaning; self-eliminating
9	Difficulty of eliminating	Simple; complicated
10	Frequency of failures	Once; systematically repeated
11	Possibilities of predicting	Unpredictable; predictable by age (accrued operating time) or by parameter
12	Origin	Design; technology; due to operation
13	Possibilities of avoiding the causes of failures	Can be avoided; cannot be avoided

handling of the attending personnel (violation of the established sequence of operations, use of inadmissible loads, work under unfavorable climatic conditions, etc.) and failures caused by elemental upheavals (icing, snow storms, bad roads, etc.).

In accordance with the causes for their appearance, failures of mechanical systems are divided into those not connected with a destruction of the system's components and failures caused by their destruction. For this, let us agree to call a "destruction" the final result of a process leading to a loss of ability to perform (wear, chipping, breakages, corrosion, aging, etc.). As an example of failures not connected with destruction can be cited the choking of the fuel supply system of transporting vehicles, leakage from built-up hoses, bracings weakened by vibrations, formation of carbon deposits on pistons, dirt or weakened contacts of electrical wires, etc. However, the number of possible failures of this type is rather small compared to the list of failures caused by some kind of a destruction.

Irrespective of their causes, any form of disruption of ability to perform on a machine must be investigated in order to avoid the appearance in the future. However, the main attention should be paid to failures caused by a destruction of parts of machines and, therefore, dependent on their service life.

The uninterrupted performances of mechanical systems are determined predominantly by their ability to withstand destruction. For example, the most bulky of the complex machines, the automobile, when designed correctly, made in accordance with modern requirements, and attended normally, represents practically an uninterrupted operating product until the appearance of gradually repeating failures caused by the destruction of its components.

A complete failure, cited in the table of classifications, means that the product cannot be used for its purpose until the failure is eliminated; a partial failure makes the partial use of the product possible. Thus, a forced stoppage of a motor caused by some impairment of its reliability is a complete failure, while its performance with reduced power or with an excessive use of lubricants is a partial failure.

A sudden failure appears unexpectedly as a result of a jumpwise change in the value of one or of several of the basic parameters of the product, i.e., as a result of a sudden complete loss by some of its components of their ability to operate; a gradual failure results from a gradual change in the values of the parameters of the product with an increasing loss of the efficiency of its components. Typical examples of gradual failures are those which result from the wear of joints. These appear gradually and lead to a gradually increasing clearance between parts and distort the correct shape of the contacting surfaces; upon reaching its ultimate wear, the joint becomes unfit. Such an event is usually preceded by the appearance of direct or indirect symptoms (knocks, larger free-play, more friction, etc.) which make it possible to predict the failure. Particular attention should be given to the widespread case of gradual destruction of parts caused by fatigue which, however, results not in a gradual, but in a sudden failure. It takes a long time, even years, for a damage due to fatigue to accumulate in a part until a crack (invisible or unnoticeable in many cases) makes its appearance; a further increase of the crack results in a sudden breakage of the part.

An obvious (explicit) failure is clearly displayed as soon as it appears or soon thereafter, while a hidden (implicit) failure may remain unnoticed for a long time. Thus, poor lubrication may not be detected until it causes a damage; a leakage in the cooling system may remain unnoticed until the unit becomes overheated; an instrument may furnish for a long time incorrect readings which are believed to be reliable.

Proceeding to failures classified by the relationship between the components, let us agree that an independent failure is one caused by any reason, except by another failure, while a dependent failure is one resulting from another failure. For example, a chip of a broken tooth of one gear may damage several parts of the transmission; a break in the crown of a valve will cause a break in the piston, bend the connecting rod, and score the cylinder of the engine; stoppage of lubrication caused by the failure of the oil pump will damage the rubbing surface of different units of any mechanism, etc. In analyzing the reliability of a product, predominant attention should be paid to independent (primary, so to speak) failures which are the primary causes of depriving products of their ability to operate. In many cases, however, the danger of the appearance of a chain of interconnected failures testifies to the vulnerability of the design, as a whole, and should be taken into consideration when estimating its reliability.

The classification of failures by consequences is reduced to dividing failures, first, into dangerous and safe, and secondly, into heavy and light. Failures threatening the life and health of people are considered dangerous, while those which are free of this menace are regarded as safe; failures resulting in heavy losses belong to the class of heavy failures; a failure is light when it causes no serious loss. The unavoidable vagueness of this division and the possibility of subjective estimates should be noted. In fact, if, say, a diesel-generator is out of order which leaves an entire region without electric power, it will indisputedly belong among heavy failures; but the consequences of a stoppage, for example, of a tractor during the rush of agricultural works which also results in an obvious, though lesser, damage may be evaluated differently. Since the division of failures of specific products into light and heavy is the job of specialists of respective enterprises or branches of industry, it is hardly advisable to demand from them an estimate to cover the entire country. It is obvious that an estimate should be recommended from the standpoint of a given enterprise and be based on the peculiarities of its products and of their operation, but when used for a branch of industry, it is desirable to assure a unity of judgement.

Note that the consequences of a failure of a machine depend at times on the circumstances at which it is used. For example, a forced stoppage of a truck during usual working conditions is, by its consequences, a safe failure, but it is a dangerous failure when the stoppage occurs during the winter in the polar regions. For machines whose work is of particular importance technically and economically during certain seasons, a failure considered as a light failure during the period between the season may prove to be a heavy failure during the heat of the season.

In accordance with the method of their elimination, failures are divided into those that can be eliminated by replacing the faulty part (this includes all cases of failures caused by destruction of parts); those that can be eliminated by adjusting, tuning, and tightening (failures caused by maladjustment of devices, weakened bracing, etc.); failures that can be eliminated by cleaning, shaking, air-blowing (failures caused by oily contacts, formation of carbon deposits, plugged pipelines, etc.); also into failures that can eliminate themselves (cutoffs). Among the latter belongs, for example, an automatic disconnection of a unit effected by its overheating caused by heavy overloading, brief plugging of pipeline supplying fuel or oil, etc.

In accordance with the difficulty of their elimination, failures are divided into simple and complicated. Among the first belong the failures that can be easily eliminated and require no prolonged and difficult repairs; among the second group belong failures that are difficult to eliminate. In connection with the subjective character of defining the difficulty of eliminating failures, definitions applying specifically to certain types of machines are desirable. For work of tractors and cars, for example, it was proposed to consider a failure to be simple when it can be eliminated with the aid of the driver's set of tools. However, when the elimination of the failure requires the use of other tools, accessories, spare parts, and also the aid of a repair crew requiring the return of the vehicle to its base (or to call for technical help), then the failure is complicated. The difference between simple and complicated failures is especially pronounced when the machine works far away from its base. Under such conditions a complicated failure may cause prolonged idleness, and, correspondingly, large losses.

According to the frequency of their occurrence, a distinction is made between singular or episodic failures resulting from random circumstances and not because they are natural and regular for products of a given model, and systematically repeating failures which, in contrast to singular failures, result from causes intrinsic to a given model, which are due to the design and its production technology.

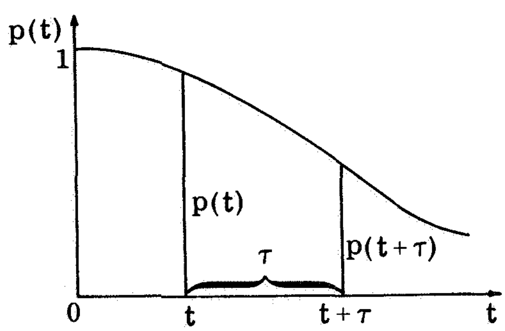
The importance of predicting failures is obvious: a failure that can be predicted makes it possible to reduce or to eliminate its consequences; in many cases, steps taken in due time can prevent even the appearance of such a failure. Certain failures are, unfortunately, unpredictable; i. e., they cannot be foreseen in advance; among them belong, in particular, the random failures whose distribution follows the exponential rule. However, the majority of failures, including those caused by destruction, can be predicted, provided their law of distribution is known. In other words, the knowledge of the regularities of distribution of failures is the key to the ability to predict them.

Predictable failures are divided into failures whose appearance depends definitely on the age of products or on the accrued time of their operation (for example, those that occur as a result of wear, aging, or accumulated fatigue), and failures resulting from a change in some parameter of the product.

The first case includes the failures of unrestored products, for which the curve of wear and tear, $p(t)$, is known (Figure 1). Here, $p(t)$ indicates the probability of no failure taking place within a time interval ranging from 0 to t. Similarly, $p(t + \tau)$ is the probability of no failure within a time interval ranging from 0 to $t + \tau$. Then, from the theorem of multiplication of probabilities, we find (provided no failures have taken place prior to moment t) that the probability of absence of failures during the interval τ will be $p(t + \tau)/p(t)$. Hence, the probability of a failure within the interval τ will be

$$Q_\tau = 1 - \frac{p(t + \tau)}{p(t)} . \tag{1}$$

Figure 1



This equation enables us to predict failures taking place within the time interval τ, when the accrued operating time t prior to this interval is known (provided no failures have occurred prior to moment t). Assume, for example, that the accrued operating time prior to the failure of an unrestored product is distributed normally with an average accrued time of 1000 hours and a deviation σ = 300 hours. At τ = 100 hours, according to equation (1), the value of Q (in percent) as a function of the accrued operating time t will be as follows[2]:

t	200	500	2000
Q_τ	0.6	5	75

The data indicate that, if a product operated for a duration of 200 hours, the occurrence of a failure during the subsequent 100 hours is hardly probable; however, after 2000 hours of operation the appearance of a failure during the subsequent 100 hours is certain. Therefore, it is expedient, as a preventive step, to replace the product not later than after it operated for 2000 hours.

In this case the distribution of the time prior to the failure follows the exponential rule:

$$p(t) = e^{-\lambda t}, \tag{2}$$

where λ is the intensiveness of the failures.

From equations (1) and (2) we obtain for this case

$$Q_\tau = 1 - \frac{e^{-\lambda(t-\tau)}}{e^{-\lambda t}} = 1 - e^{-\lambda t}; \tag{3}$$

i.e., Q_τ is independent of the accrued time t, which indicates that it is impossible to predict failures by basing the prediction on the accrued operating time.

The forecasting of failures based on a parameter can be applied, for example, for automatic metalworking machine tools and dimension-checking facilities. The most important parameter of a machine tool or of a device is the precision with which a given operation is executed under certain working

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[2]Shor, Ya. B., "Statistical Methods of Analysis and Control of Quality and Reliability," Sovetskoye Radio (Soviet Radio), 1962.

conditions. An index of precision that does not meet the established limit indicates a lost ability to operate, i. e., a failure. Such a failure can be predicted by the value of the parameter of precision, keeping in mind that this value varies with the increase in accrued operating time and its approach to the limit of tolerance enable us to judge a coming failure.

In many cases, failures caused by destruction (wear) can be considered to belong among failures whose prediction is based on a parameter. The coming of a failure can be judged by watching the wear of a part.

In analyzing and preparing steps for elimination of failures, it is important to determine their origin (defects in design, production technology, or in operations) and then to divide the failures into those that can and cannot be eliminated (correctable and irreparable). Among the correctable failures belong those connected with the design and technology and are more often disclosed during the "working-in" and finishing of new products. The failures due to design are caused by defects in the latter and can be eliminated by a better design; failures due to technology are caused by defects in production technology or by defective technological control and can be eliminated by improving the technology and inspection methods in production.

The causes of correctable failures can be eliminated entirely or neutralized to a degree that will make the appearance of a failure possible only after the amortization date of the service life of the machine. For example, artificial aging of housing parts eliminates their deformation caused by internal stresses; the use of stainless steel or of polymer substances prevents their destruction by corrosion; the use of modern methods of designing, production, assembly, and arresting of threaded products can practically eliminate the failures caused by weakened threaded joints or by unscrewing of parts; many machine parts can be so designed and made that no repairs will be needed during their work.

The irreparable failures include those for which a method of their elimination has not yet been found, or whose elimination requires an economically unjustified cost. For irreparable failures, the problem is reduced to finding means that will assure their recovery in due time or that will reduce their consequences.

The division of failures by their origin is often connected with difficulties and is not always indisputable. For example, the breakage of a transmission gear may be caused by a defective assembly of the unit or by the heat treatment of the gears; however, it does not eliminate the possibility that it was caused by an inadequate margin of strength. The cause of a broken crankshaft of an engine may be due to the inadequate margin of strength, but it may also be due to an excessively unbalanced mass of the flywheel, couplings, and of other parts connected to the crankshaft; it is also possible that the strength of the crankshaft is reduced by some technological concentrator of stresses or by residual stresses appearing during the trueing of the crankshaft between operations. A rapid wear of some joint may turn out to be the result of defective design or technology, but it also may be due to the violation of the rules for lubrication by the attneding personnel. For this reason, the determination of the causes of failures in complicated cases requires a thorough study of all possible sources.

This classification of failures, while covering most of the items used in machine-building practice, is not yet exhausted. In certain special cases and fields it may prove to be advisable to separate other classifying symptoms or to use a more detailed classification. For example, I. N. Velichkin suggested that the failures of tractor engines should be divided in accordance with the difficulty of their elimination into correctable without replacement of parts and without dismantling the engine; failures whose elimination will require the displacement of parts without even a partial dismantling of the engine (i.e., without removing parts which open the inside space of the engine), partial dismantling of the engine by opening its inside space with none of its pistons removed, overhauling of the engine, major repair of the engine; and failures leading to discarding the engine.

When used, cases sometimes happen in which a machine is unexpectedly unable to perform any operation or it performs it with interruptions. For example, a transporting vehicle begins to skid on a bad road, a tractor meets increased resistance of the soil and fails to plow to the needed depth, and units of an agricultural harvesting machine become packed with straw. Such events can be regarded as failures only when a given model is especially designed for a given operation performed under exactly such conditions.

Mention should be made of defects in products which do not impair its ability to perform, i. e., a product meets the established requirements, inasmuch as the basic parameters are concerned, but does not satisfy the parameters of secondary importance (such as, for example, the external appearance, convenience of operation, etc.). As it follows from the definition of this concept, such violations of fitness are not failures; there are, however, exceptional cases in which an unfit item is not allowed to work by the existing rules; i. e., essentially, it is made unworkable. For example, a defective control instrument showing the state of some important unit of a machine, or the course of a process performed by it, may not affect the workability of the machine, but a continuous work of the machine may cause a breakdown or considerable damages and should be discontinued.

Should all failures and defects be registered? In our opinion, all of them. This, however, can be accomplished only by tests and operations carried out and observed by a special personnel; in ordinary operations, the information arriving from consumers does not in the majority of cases contain data on failures and defects of secondary importance.

Let us consider the sequence of the work on a most difficult case of systematization and processing of complete information on a variety of failures in a large group of complex, multi-component machines (of the same model).

The work should be started by selecting the groups which are expedient in this case for classifying the failures; this will depend on the purpose and features of the product and also on the purpose of the investigation.

For a study of failures of mass-produced machines (autos, tractors) it is desirable to use at least five groups of failures classified by the reasons for their appearance, relationship between the failures of components, consequences, difficulty and possibility of eliminating the causes of the appearance of failures (groups 2, 6, 7, 9, and 13). Classification of the failures by the frequency of their occurrence and by the possibility of their prediction can be easily accomplished at the concluding stage of the intestigation by using the results obtained by processing the information.

Next, after separating the failures from defects (which are to be analyzed separately), it is necessary to start the by-component selection of the failures and for this it is recommended that all basic information on each of these failures be recorded on separate cards (in particular, the name of the component that failed to perform, the name and character of the failure, the accrued operating time prior to the failure, the circumstances of its appearance and consequences of the failure, list of work and of the time spent for its elimination, list and cost of replaced parts, and the numbers of the groups of the employed classification of failures). For a large volume of information and with a suitable form of recording (and using a code), the information recorded on the cards can be processed by a machine.

The data and the entire analysis of reliability must be processed by proceeding from particular to common (general) by following the "part-assembly-unit-machine" pattern. The result will be a list of failures for each part, for each assembly and unit. Arranging all cases in an order of increasing accrued operating time prior to the failure, the respective statistical characteristics are calculated for each failure.[3] Next are plotted illustrative curves

[3]Shor, Ya. B., and Kugel', R. V., Indicators of Reliability of Industrial Products ("Pokazateli nadezhnoisti promyshlehnykh izdeliy"), Collection

of the distribution of the accrued operating time prior to the failure (the accrued time is laid off on the abscissa and the frequency of failures on the ordinate) and the curves of the decreases (with the accrued operating time prior to the failure laid off on the abscissa and the percent of products continuing to work without failures laid off on the ordinate). The ordinate of the curves of decreases indicates the probability of uninterrupted work for the selected accrued operating time.

For unrestorable machine components, which are replaced immediately after the first failure, the characteristics of uninterrupted performance obtained in this manner coincide with the characteristics of long service life. For components restored during the operation, these characteristics do not coincide; therefore the service life of such components must be characterized separately and be based only on the information about those failures which were caused by some process of destruction (for this, the second group of classifications listed should be used).

The processed data of a fairly large group of machines provide a complete statistical picture about the failure-free feature and the service life of the components of a machine model investigated under specific testing and operating conditions (only statistical estimates must be used because the attempts, which are frequently used in practice to estimate the reliability, when based on the data obtained from a small group of machines, will provide neither complete nor reliable results).

The reliability of a machine cannot be characterized by a simple summation of all observed failures of its components. The results of analyzing failures in accordance with the proposed method make it possible in the majority of cases to divide the failures into essential and unessential (an unessential failure is one which is quickly detected and quickly eliminated). Unessential failures can be occasionally excluded from the overall estimate of the reliability of a complex machine; also frequently excluded are the failures disclosed and eliminated by the preventive inspections provided by the instructions of the manufacturing plant; other limitations depending upon the special features and the purpose of the machine are also possible.

Therefore, an analysis of failures must cover several subdivisions in order to obtain a fairly complete estimate of the reliability. Only in doing so will it be possible to obtain information on relationships between various failures, for example, between essential and unessential, dangerous and safe,

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of Articles on Standardization and Improvement of Quality of Industrial Products, Izdatel'stvo Standartov (Publishers of Standards), 1965.

and simple and complicated; it also makes it possible to calculate the pre-failure accrued time, for example, per any failure, per essential failure, and per dangerous failure; also to analyze the regularity of distribution of failures to obtain the prerequisites for a thorough analysis of causes and consequences of failures, etc. To make it short, the obtained picture is by far more complete than the one obtained by simply recording the failures without a detailed classification.

In conclusion, worthy of attention is the great practical importance of accounting and analyzing machine failures while a machine is operating. Precise information on failures enables us to estimate the ability of machines to operate without failures; information on failures caused by destruction of parts enables us to estimate the service life of machines and to know exactly the rate of spending spare parts; information on difficulty, duration, and cost of technical service and repairs needed to prevent and eliminate failures enables us to estimate the repairability of machines. The sum total of this entire information provides an objective picture of the reliability of such machines and makes it possible to find the means of improving it.

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13. ABSTRACT

Because of the increased attention paid to the problem of reliability of machine-building products, to organization of tests and observation of the performance of products in operation, and also to the analysis of the results of observations by using the methods of the theory of reliability, there inevitably appears a series of problems pertaining to the nature of failures, their classification, recording, and analysis. Discussed in this paper are the fundamentals of these problems; for example, what is a failure, can any specific event be regarded a failure? How should the failures appearing during the operation of a complex multicomponent machine be classified? Do all failures deserve the same attention, accounting, and recording? Which of the failures should be used as a basis for estimating the faultless performance and the service life of a machine?

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Sudden failure						
Gradual failure						
Explicit failure						
Implicit failure						
Dependent failure						
Independent failure						
Dangerous failure						
Safe failure						
Heavy failure						
Light failure						
Singular failures						
Episodic failures						